Importance-Aware Lighting Design in Volume Visualization

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***Abstract*—Lighting design plays critical roles in depicting structural details in volume rendering. Insufficient and excessive illumination can both affect effectiveness of presenting structural details in visualization. This paper introduces topological importance into the lighting design and proposes the importance-aware lighting. In the proposed approach, the lighting in volume rendering is enhanced based on topological importance. As a result, importance of structures can be depicted from the lighting perspective. The contour tree, one of topological data structures, is used to represent topology in this paper. Topological importance such as persistence derived from the contour tree is used to modulate lighting coefficients. The experimental results demonstrate that the importance-aware lighting not only helps to depict structural details more clearly but also reveal topological importance of structures in rendering. The importance-aware lighting is more meaningful to users but not a random selection without physical meanings based on preferences.**

I. Introduction

The ultimate goal of volume visualization is to provide useful insights into volumetric data. Direct volume rendering is one of effective and flexible visualization methods for three-dimensional volumetric data. It usually regards each voxel as a radiance emitter with a certain level of density. The mapping from each voxel as well as features to different optical properties (e.g. colors and opacities) is specified by transfer functions. As a result, the basic structure information of volume data can be presented in a rendered image without using any external lighting. In volume rendering, once the transfer function and the viewpoint are defined, the visual perception of object features in the volume is mainly decided by lighting parameters [1]. Realistic illumination in volume rendering helps users get better 3D shape perception [2]. Insufficient and excessive illumination can both affect effectiveness of presenting structural details in visualization [3]. Lighting is highly necessary in improving effectiveness of volume visualization. Local illumination models, such as Blinn-Phong primarily reveal the structural shape and local details, while global illumination models further depict the occlusion relationships between structures through mutual shadowing [1]. In Lindemann et al.'s user study [4], the effectiveness of seven states of the direct volume rendering techniques is measured and showed that global illumination models help in assessing depth and size in images. Ropinski et al [5] demonstrated that by using realistic lighting, observers use less time and are more accurate at assessing depth in a volume rendering. Therefore, similar to transfer functions, lighting design plays critical roles in depicting structural details in volume rendering.

Extensive research has been investigated in previous work on lighting in volume rendering ranging from early optical model design [6] to recent optimization of lighting based on structure [1] and perception [7]. Despite various lighting parameters (e.g. lighting source position, ambient, diffuse, and specular coefficients) and data features (e.g. scalar values, gradients) being used, most of conventional approaches highly focus on generating renderings with more realistic appearances. These may mislead users from the ultimate goal of volume rendering, i.e. drag users from getting useful insights of volume data to creating colorful images. Moreover, lighting is still defined based on user's preferences in most cases. Thus, a lighting design approach depicting importance differences of various structures is highly desirable in order to allow users perceive importance of structures from the lighting perspective.

Furthermore, topology has been an important tool for analyzing scalar data and flow fields in visualization. Topological features of a field are characterized by its critical points. In addition to providing topological features of a volume [8], topology has been used to generate transfer functions in volume rendering [9], [10], [11] as well as other applications such as image segmentations [12]. More interestingly, topology can intrinsically represent importance of structures with various topological measures of importance [13]. All these work motivates us introduce topology into lighting design in volume rendering in order to depict importance of structures from the lighting perspective. The principal technical challenges for this problem include how topology can be used in lighting design and what are the relations between topology and lighting parameters.

This paper introduces topological importance into the lighting design and proposes that lighting in volume rendering can be enhanced based on topological importance. As a result, importance of structures can be depicted from the lighting perspective. The contour tree, one of topological data structures, is used to represent topology in this paper. Topological importance such as persistence derived from the contour tree is used to modulate lighting coefficients. The advantage of the proposed approach is that the importance-aware lighting not only helps to depict structural details more clearly but also reveal topological importance of structures in rendering.

The paper is organize as follows. We first introduce the previous work on lighting design and topology in volume rendering in Section II. Section III briefly surveys contour trees as one of data structures used to explicitly store topological features. Section IV defines measures of importance from topological perspective. The approach of importance-aware lighting is described in details in Section V. Section VI gives experimental results and discussions. Finally, we conclude the paper in Section VII.

II. Related Work

Extensive research has been investigated in lighting design in volume rendering. Conventional approaches often focus on creating realistic images such as ray tracing based techniques. Different from the conventional lighting model with constant lighting coefficients, Lum and Ma [14] proposed the concept of lighting transfer function (LTF) which modifies the conventional lighting model by defining ambient, diffuse, and specular lighting coefficients with look-up tables that are functions of two scalar values along gradient direction. However, as conventional transfer function approaches, [14] does not give any approaches on how to depict importance of structures effectively from the lighting perspective. Because far-range scattering effects usually provide negligible contributions to a given location due to the exponential attenuation with increasing distance, [15] presents an ambient scattering model by preintegrating light transport in spherical subvolumes by means of a Monte-Carlo simulation. [2] develops a framework that applies Monte Carlo ray tracing (MCRT), coupled with physically based light transport to direct volume rendering to create realistic volume rendering. [16] takes into account view and transfer-function dependent content of the volume data to automatically generate an optimized three-point lighting environment under global illumination. Wang et al. [7] divided the lighting effects into global and local effects to enhance visual perception in volume rendering. Gradient and shadow information are used for the perception enhancement. However, these approaches do not consider importance in lighting design.

On the other hand, Carr et al. [17] defined local geometric measures as importance measures to simplify topology. Zhou et al. [13] further utilized multiple measures of importance to simplify topology. Besides the topological simplification based on various measures of importance, topology is also used to generate rendering parameters. For example, Zhou and Takatsuka [11] proposed an approach which uses topological features to automatically generate transfer functions. However, few work considers topology in lighting design in order to depict importance of structures from the lighting perspective.

III. Contour Tree Revisited

A. Definition of Contour Trees

Topology has been an important tool for analyzing scalar data and flow fields in visualization. Two data structures are commonly used for explicitly storing topological features: Morse-Smale (MS) complexes [18] and Reeb graphs [19]. The MS complex decomposes domain of a function into regions having uniform gradient flow [20]. The Reeb graph [19] is a simple structure that summarizes the topology of a Morse function. It traces components of isosurfaces/contours as they sweep the domain. For functions with simply connected domains, this graph is also simply connected and called the *contour tree* (CT). This paper focuses on the contour tree for storing topological features.

The concept of isosurface/contour is used to set up the contour tree. Consider a continuous scalar field $\mathbb{F}$ defined on a domain $\mathbb{R}^d$, $f: \mathbb{R}^d \to \mathbb{R}$. $\mathbb{R}^d$ is assumed to be a simplicial complex. For a point inside a simplex, its function value is a linear interpolation of the values on the vertices. The *functional range* of the field $\mathbb{F}$ is the interval between the minimum and maximum values of the function f , $[f_{min}, f_{max}]$. For a scalar value $h \in [f_{min}, f_{max}]$, the *level set* of the field $\mathbb{F}$ at the value h is the subset $L(h) = \{(x) \,|\, f(x) = h\}$. While h scans monotonically through the entire range of $\mathbb{F}$ from f_{min} to f_{max}, the topology of the level set changes only at the *critical points* of $\mathbb{F}$. As h increases in the level set of $L(h) = \{(x) \,|\, f(x) = h\}$, contours appear at local minima of f, join or split at saddles, and disappear at local maxima of f. If each contour is represented as a *node*, the evolution of the level set forms a tree called *contour tree*. Therefore, the contour tree traces components of isosurfaces as they sweep the domain. It represents the nesting relationships of connected components of isosurfaces [21], [10].

Typically, the contour tree is represented as a list of *nodes* and a list of *arcs*, where each arc is defined as a node pair. The nodes of the contour tree correspond to critical points of a scalar field and are therefore associated with their critical values. Pascucci et al. [22] used an alternative *branch decomposition*, where a *branch* is defined as a monotone path in the graph traversing a sequence of nodes with non-decreasing (or non-increasing) value of the scalar field.

B. Contour Tree Indexed Subregions

Since the concept of flexible isosurface [17] supports independent manipulation of single contours, the contour tree can be used as a visual index to segment data set into different zones/subregions. Weber et al. [10] extended this idea in volume rendering and proposed a volume rendering framework which classifies volume data based on the contour tree and assigns unique transfer function to each subvolume corresponding to a branch of the contour tree. Our work uses the contour tree not only to index various subregions, but also define lightings to subregions according to importance of subregions based on topological features derived from the contour tree.

IV. Topological Importance

A. Definition of Importance

In the Merriam-Webster dictionary [23], importance is defined as: *Importance means a quality or aspect having* *great worth or significance. It implies a value judgment of the superior worth or influence of something or someone*. It describes the quality (positive or negative) that renders something desirable or valuable, and worthy of note.

In topology, we define importance as follows: *importance* suggests an evaluation or judgment of significance of an object in a data set. It describes the quality that renders an object desirable or valuable, and worthy of note in visualization. This quality is represented by some measures that evaluate the degree of an object which draws attention to viewers in visualization. In the lighting design in this paper, importance is a value that indicates object's significance. The object is indexed by branches in the contour tree. Thereofe, branches with higher importance are candidates to be emphasized with the lighting.

B. Evaluation of Importance

In contour trees, each branch corresponds to a region in the data domain. The importance of each region can be depicted using different measures. The importance of one object is related to different features of the scalar field, e.g. scalar value, size, position, and their combinations. The persistence p, volume v and hypervolume hv belong to measures derived from the data set itself. Persistence is equal to the absolute difference in scalar values of two critical points. Volume is the voxel count of the region enclosed by the isosurface. Hypervolume is the integral of the scalar field over the enclosed region.

From the physical point of view, persistence, volume and hypervolume describe the importance of a branch from different physical aspects [13]. For example, when we think the scalar value of each voxel as the mass of that voxel, the importance described by hypervolume is based on the mass of the region corresponding to a branch, i.e. what the weight of a branch is. While persistence describes importance based on the number of steps of the sweep for which a feature retains its topological uniqueness, and volume describes the importance based on the size of the region corresponding to a branch.

V. Importance-Aware Lighting

A. Lighting Model

Various illumination models are available for volume rendering. Without loss of generality, this paper considers the classical Blinn-Phong local illumination model as the basis of the proposed approach. According to Blinn-Phong model, the color of a rendered voxel can be computed as:

$$C = (k_a + k_d\,(\mathbf{N}\cdot\mathbf{L}))\,C_{tf} + k_s(\mathbf{N}\cdot\mathbf{H})^n \tag{1}$$

where k_a, k_d, and k_s are the ambient, diffuse, and specular reflection coefficients respectively, n is the shininess exponent, C_{tf} is the color from the transfer function, $\mathbf{N}$ is the normalized gradient direction of the voxel, $\mathbf{L}$ is the normalized light direction, and $\mathbf{H}$ is the normalized half-way direction. k_a determines how much ambient reflect is actually reflected. k_d is the amount of diffuse light reflected. k_s is the amount of specular light reflected. k_a, k_d, and k_s are usually restricted in $[0,1]$.

Our work uses this model as the basis to incorporate topological importance into the lighting design pipeline.

B. Topological Importance and Lighting Design

Typically, ambient reflection is used to simulate the "radiant" effect in lighting, that is, the effect of light which is "bouncing around" the environment which otherwise is not accounted for by the lighting model. It comes from different light sources and is also scattered in different directions. Diffuse reflection is used to simulate re-emission from a surface where the re-emittance is not "ordered". It is the most instinctive meaning of the lighting of an object. Specular reflection is used to simulate mirror-like reflection of light of an object. Based on these basics, this paper focuses on modulating diffuse reflection with topological features in order to emphasize importance of structures from the lighting perspective.

From the lighting model as presented in Equation 1, the contribution of different reflections can be controlled with k_a, k_d, and k_s respectively. Furthermore, as mentioned in the previous section, the importance of structures can be described with topological measures of importance. Therefore, this paper introduces topological importance into the lighting design by defining diffuse reflection coefficient as a function of topological importance.

$$k_d = f(I_n) \tag{2}$$

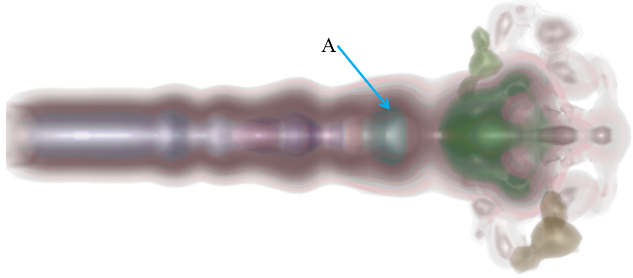
where f is the function of I_n, I_n is normalized topological importance value of p_n, v_n, or hv_n. In the importance-aware lighting model, k_a and k_s are defined by the user in advance and same for all structures. Therefore, the variations of lighting in the rendering are mainly decided by k_d, which reflects importance of structures based on topological features.

VI. Experimental Results and Discussions

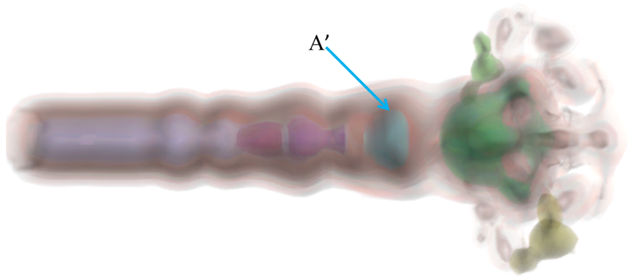
We conducted experiments on various data sets to demonstrate the effectiveness of the proposed approach in volume rendering. Our system was run on Ubuntu platform on a MacbookPro machine (Intel Core i5 2.53 GHz, 2G RAM) equipped with an NVIDIA GeForce GT 330M graphics card.

We firstly used the proposed approach to render the "fuel" data set, a $64 \times 64 \times 64$ voxel data set resulting from a simulation of fuel injected into a combustion chamber, see http://www.volvis.org/. Fig. 1(a) shows the result using the proposed lighting approach. Fig. 1(b) rendered structures using conventional approach where all structures were rendered with the same diffuse reflection coefficient without importance information. Both Fig. 1(a) and Fig. 1(b) used the same transfer functions. Normalized persistence was used for k_d in this experiment. From the comparison of Fig. 1(b) and Fig. 1(a), it can be seen that the proposed approach can help to emphasize structures with high topological importance, especially make inner structures more clear (e.g. the object pointed by A in Fig. 1(a) compared with the object pointed by A' in Fig. 1(b)).

We also applied the proposed approach to render the "neghip" data set, a $64 \times 64 \times 64$ voxel data set resulting from a simulation of the spatial probability distribution of

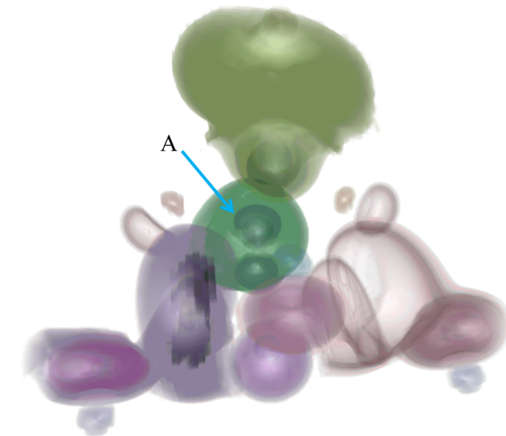


(a) Proposed approach

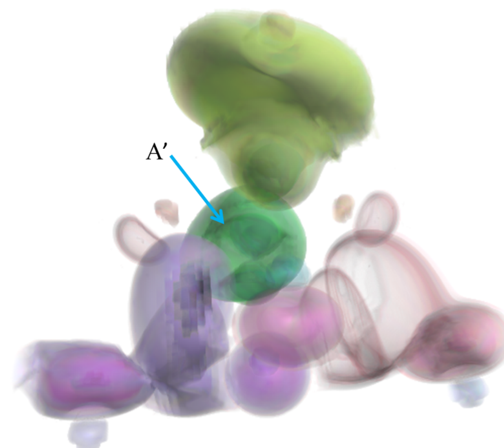


(b) Conventional approach

Fig. 1. Volume rendered fuel data set using different lighting approaches.



(a) Proposed approach



(b) Conventional approach

Fig. 2. Volume rendered fuel data set using different lighting approaches.

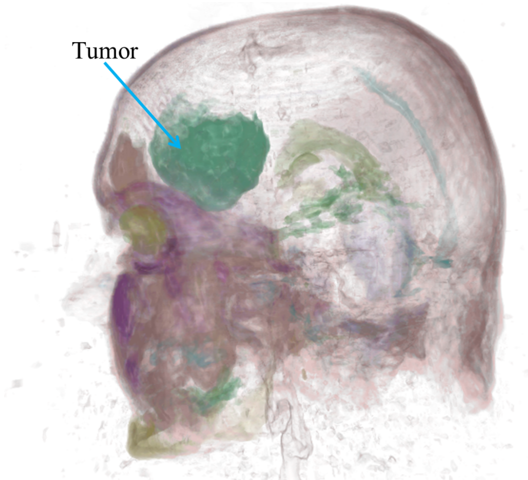
the electrons in a high potential protein molecule, see http://www.volvis.org/. Fig. 2(a) shows the result using the proposed lighting approach. In Fig. 2(b), structures were rendered using conventional approach without importance-aware lighting. Both Fig. 2(a) and Fig. 2(b) used the same transfer functions. Normalized persistence was used for k_d in this experiment. The comparison of Fig. 2(a) and Fig. 2(b) show that importance-aware lighting clearly depicted inner structures with more details that conventional approach cannot (e.g. the comparison of A in Fig. 2(a) and object pointed by $A^{'}$ in Fig. 2(b)).

The proposed approach was also applied to a more complicated data set, an MR head data set with brain tumors inside (data courtesy of B Terwey, Bremen). In the MR head data set, brain tumors are often difficult to be visualized because of inclusions of tumors inside the brain and complicated brain structures. In this experiment, transfer functions were generated with the approach presented in [11] in order to render tumors in the brain. In Fig. 3(a), structures were emphasized using the proposed lighting approach with the normalized persistence as k_d. Fig. 3(b) shows the rendering result without importance enhancement in lighting. Both Fig. 3(a) and Fig. 3(b) used the same transfer functions. Compared with Fig. 3(b), Fig. 3(a) shows that importance-aware lighting highlighted structures such as tumors more obviously. Despite the differences being not so high as in renderings of “fuel” and “neghip” data sets, the tumor in Fig. 3(a) was still emphasized for its importance from the lighting perspective.

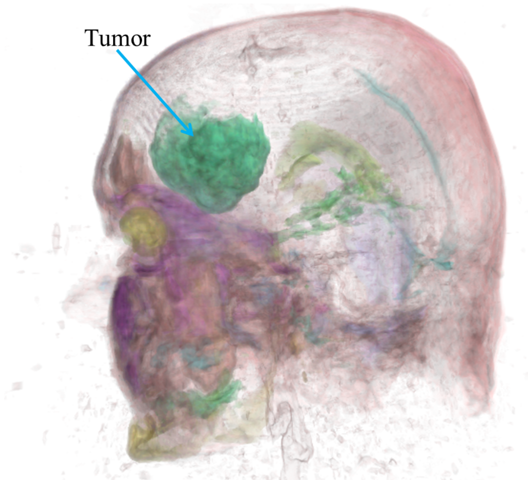
The experiments demonstrated that the proposed approach can effectively emphasize structures from the lighting perspective based on topological importance. Compared with conventional methods, importance-aware lighting has following advantages: 1) It enhances structural importance from the lighting perspective besides the description of structural details; 2) The lighting in rendering is more meaningful to users but not a random selection without physical meanings based on preferences.

VII. Conclusions and Future Work

This paper proposed an importance-aware approach for lighting design in volume rendering. The contour tree was used to represent topological structures of data sets and topological importance was used to enhance lighting in visualization. The advantage of the proposed approach was that the importance-aware lighting not only helps to depict structural details more clearly but also reveal topological importance of structures in rendering. The future work of this research will focus on investigating more flexible approaches to incorporate topological importance in lighting design.



(a) Proposed approach



(b) Conventional approach

Fig. 3. Volume rendered tumor head data set using different lighting approaches.

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